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Army Blast Claims Evaluation Procedures

William F. Wright

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The U.S. Army engages in firing activities on Army reservations throughout the United States. These activities are essential for research, equipment performance verification tests, personnel training, and the disposal of obsolete ammunition. Unfortunately, persons who reside nearby are subjected to side effects in the form of noise, vibrations, and occasionally, property damage. When a particular Army reservation is informed that property damage has occurred, the Army advises that a claim for restitution can be submitted. The claim is them processed through a procedure which leads to final settlement. This report is concerned with describing the major facets of the technical review process which has been instituted to develop an opinion as to Army responsibility.

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1. INTRODUCTION

1.1 Purpose. The United States Army engages in firing activities on Army reservations throughout the United States. These activities are essential for research, equipment performance verification tests, personnel training, and the disposal of obsolete ammunition. Unfortunately, these firing activities subject nearby residents to noise and can damage their properties. When a particular Army reservation is informed that property damage has occurred, the Army advises that a claim for restitution can be submitted. The claim is then processed through a procedure which leads to final settlement. This report describes the technical review process which has been instituted to assess Army responsibility.

1.2 Types of Firing Activity. The Army firing activities consist of aerial bombings, artillery firings of live and inert ammunition, and detonations of high explosives (HEs). Artillery weapons are fired for testing performance capability, but most firings are for the purpose of training both regular and reserve forces. The sizes of weapons range from 105-mm caliber rounds up to the 8-in rounds. Blast effects are produced by detonations of HE rounds in designated impact areas and by propellant gases escaping from muzzles of weapons at their firing points. Bombing exercises are conducted for training purposes. The primary bomb used is the MK-82 which weighs about 500 lb and contains 192 lb of explosives.

In addition, for training purposes, the Army Corp of Engineers perform demolition exercises. Especially at ammunition plants, the Army has the task of disposing of obsolete ammunition and other explosive waste. This is accomplished by performing what is referred to as a demilitarization (DEMIL) operation which consists of detonating explosives in earth pits with several feet of dirt cover.

On occasion, various miscellaneous firing activities are conducted that are not a part of any regular training or testing program. The most important of these is the necessity to dispose of old, obsolete munitions found on and off of Army reservations. These munitions, being old and unstable, are dangerous and must be prepared for detonation with a minimum of movement. Therefore, the process is accomplished in place if possible. On several occasions, fishing vessels in the Gulf of Mexico have snagged old bombs in their nets. These bombs are usually detonated in place.

1.3 Types of Property Damage. The spectrum of the variation in damage claims is broad. However, a fairly systematic procedure for evaluating arbitrary claims has been developed which ensures reasonable consistency. Damages to private properties are categorized as structural or displacement. Structural includes all damages to integral parts of homes or business properties. Displacement includes the knocking or jarring of items from shelves, wall attachments, or racks. In these cases, the initial displacement can lead to collateral damages when displaced items impacts other vulnerable articles. Table 1 lists examples of damage which have been cited by claimants as caused by Army firing activities.

Table 1. Spectrum of Claimed Property Damage

Structural Damage	
Thermoplane windows/doors	seal ruptures
Window/door glass panes	cracks/shattered
Interior walls	cracks, nail popping, paint peeling
Interior/exterior brick work	cracks
Basement walls, foundations & footings	cracks
Patio/walks/slabs/swimming pools	cracks
Wells/cisterns	cracks
Skylights	cracks
Displacement	
China closet glass shelves	dislodged
Objects	displaced from shelves/racks
Mirrors/pictures	dislodged from walls
Mobile homes	displaced
Structures/porches/doors	misalignment

2. BLAST DAMAGE MECHANISMS

2.1 Overpressure Due to Detonations. A potential mechanism for causing damage to property are vibrations created by the imposition of a low-level air overpressure pulse. Overpressure is a level of force exerted on the surface of structures. As the name of this parameter implies, it is a measure of atmospheric pressure above the ambient level. In reality, the parameter of interest is overpressure exerted over a period of time called the "applied pulse." But, since the duration of the typical pulse is relatively constant, it is feasible and convenient to relate damage directly to overpressure levels.

The overpressure in question can be caused by a detonation of some kind of HE. Initially, the detonation produces a concentrated high-pressure volume of gases which subsequently expands radially in all directions from the point of origin (assuming no obstructions). As the gases expand, the forward edge of the expanding volume interacts with the ambient air such that a highly compressed layer of air is created—called the "shock front." A typical pressure waveform for the phenomenon is presented in Figure 1. The overpressure curve at the shock front is almost discontinuous between the ambient pressure level preceding the front and the peak overpressure at the front. However, there is a short period—called the "rise time"—between ambient and the peak value at the front. Behind the shock front, the overpressure gradually declines as a function of distance toward the center of the explosion and eventually drops below the ambient pressure. That point marks the end of the positive phase duration. The negative phase reflects the reduced air density caused by the air having been swept from the volume during the creation of the shock front. Thus, in the near field (close to the energy source), the disturbance has the form of a classical shock wave where the disturbance includes the massive outward flow of air particles from the center of detonation.

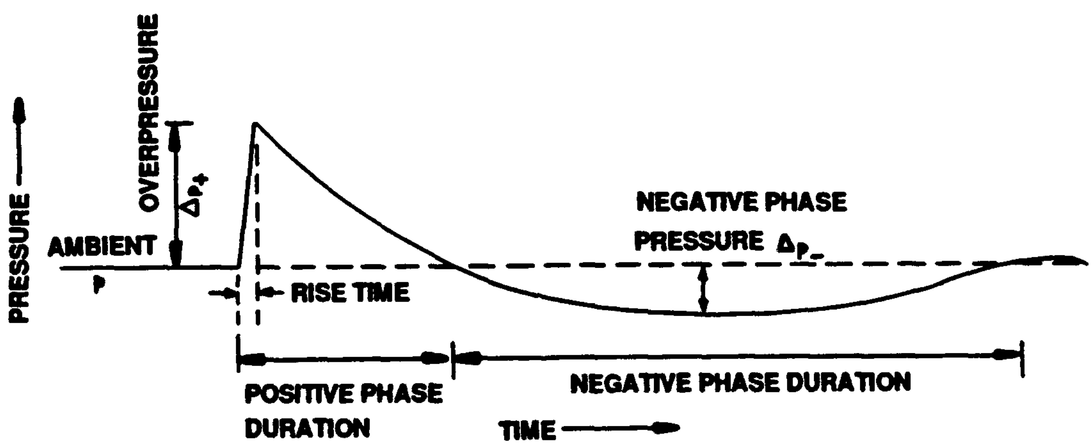

Figure 1. Pressure-time waveform in the near field due to an explosion.

The classical shock wave is rather quickly transformed to a sound wave. Its waveform is demonstrated in Figure 2. Unlike the shock wave in the near field where damage is caused by materials yielding directly to the applied overpressure, the wave in the far field causes damage by creating structural vibrations. Civilian properties associated with damage claims are usually located in the far field (miles from the source or center of detonation). Consequently, the phenomenology involved with regard to a typical claim consists of induced vibrations caused by an applied overpressure pulse.

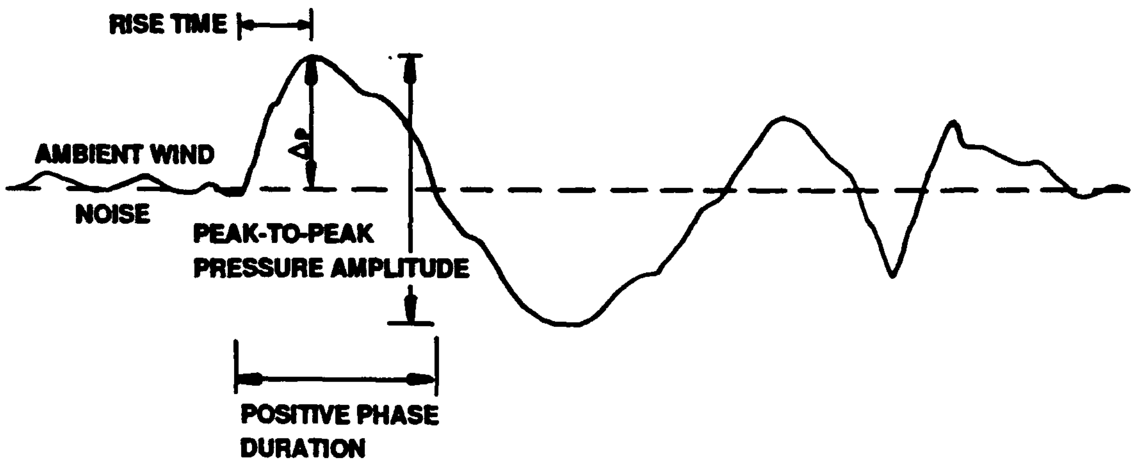

Figure 2. Pressure-time waveform in the far field due to an explosion.

In the near field, the unit used to express overpressure is normally the pound per square inch (lb/in^2), or, if in the metric system, the kilopascal (kPa). But, in the far field, the unit used is the Pascal (Pa), due to the low overpressures involved. The practicality of this convention can be realized on considering that 1 psi equals 6,895 Pa and the levels involved for most claims range from a few Pascals up to 1,000 Pa in extreme cases. Since the subject of this report is closely related to sound propagation, several discussions involve the unit decibel (db) which is most appropriate to the study of sound. Conversion from Pa to db can be accomplished by using the following relation:

$$P_{db} = 20 \log_{10} [P_{Pa} / P_0] \quad . \qquad (1)$$

Where:

P_{db} is the overpressure expressed in db,

P_{Pa} is the overpressure expressed in Pa, and

P_0 is a reference overpressure for 0 db = 20×10^{-6} Pa.

2.1.1 Effects Attributable to Meteorological Conditions. The characteristics of overpressure-wave propagation in the far field varies significantly as the result of existing meteorological conditions. For example, the disturbance can be perceived at a given location from the center of detonation as being very intense in one instance and at another time hardly noticeable at the same location after a similar detonation. In effect, the disturbance in question in the far field is essentially a sound wave and, therefore, the physics involved in its propagation through the atmosphere are those associated with sound propagation. The meteorological conditions existing throughout the area at the time of the detonation determines the wave's propagation velocity at various altitudes. The most important parameter affecting the propagation is the change in the velocity of sound as a function of altitude (velocity gradient). The sound wave is refracted to produce magnification or reduction at specific distances on the ground measured from the center of detonation. In turn, the pertinent atmospheric variables which affect sound velocity are temperature and wind velocity (humidity has a small effect, but can be neglected).

In the absence of wind, sound velocity can be determined by the following expression:

$$C = 72.228 \sqrt{K} \ (km/h) \qquad (2)$$

where K is the absolute temperature. This equation defines the relationship of sound velocity with absolute temperature, which is a nondirectional parameter. Wind effects on the sound velocity are directional. That is, in the downwind direction, the sound wave velocity is increased by the wind velocity and, in the upstream direction, the opposite effect occurs with sound velocity being reduced. More precisely, sound velocity with respect to the ground (at any given altitude) can be determined by the following equation:

$$V = C + U \cos\theta \qquad (3)$$

where C is sound velocity as determined by Equation 2, U is the wind velocity for the altitude of interest, and θ is the angle between the downwind direction and the direction for which the sound velocity is desired.

A representation of the propagation of the overpressure wave under the atmospheric condition of a constant temperature with altitude and no wind is shown in Figure 3. The wave is considered to be made up of a number of rays (sound rays) propagating from the center of detonation with departure angles above the horizon distributed equally in space. As the diagram indicates, the sound rays will, under these conditions, propagate radially out in all directions with equal speeds. Sound velocity is, in this case, constant with respect to altitude; thus, the velocity gradient is zero. To first order effects, the sound wave intensity (overpressure) will be degraded as a function of increasing distance only due to spreading (inverse square law). The situation is different if the sound velocity gradient is positive, negative, or if several gradients are present.

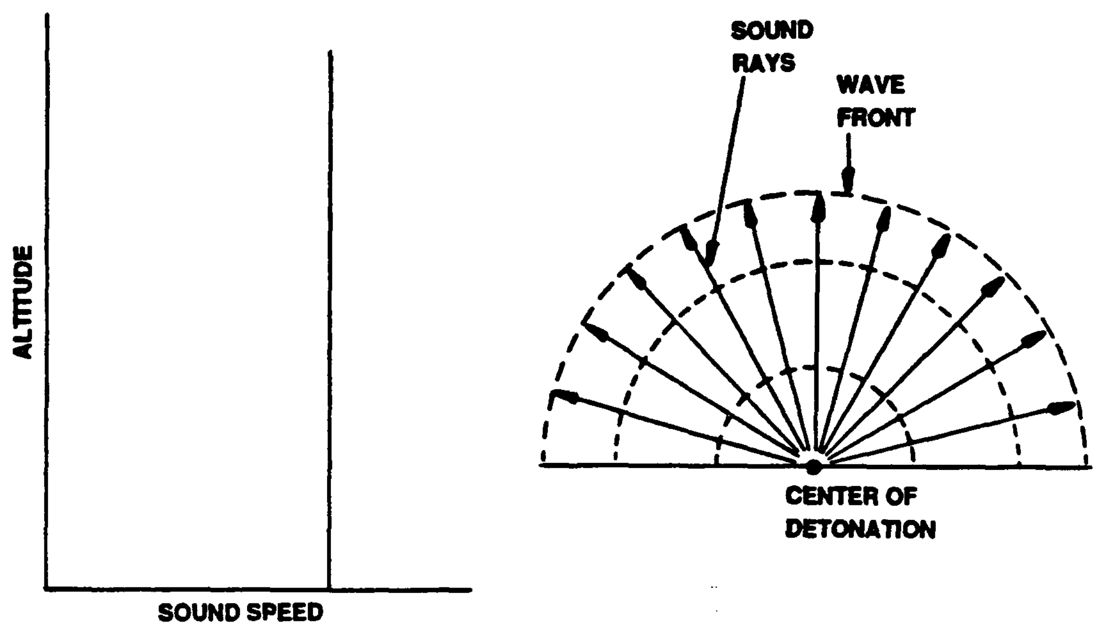

Figure 3. Sound wave propagation from a detonation on the earth surface with zero atmospheric temperature gradient and no wind.

The sound ray refraction for the case where a single negative sound velocity gradient is present is demonstrated in Figure 4. The interaction is such that all sound rays are turned upward, and, within a relatively short distance from the center of the detonation, there are no effects. That is, the disturbance cannot be heard or felt.

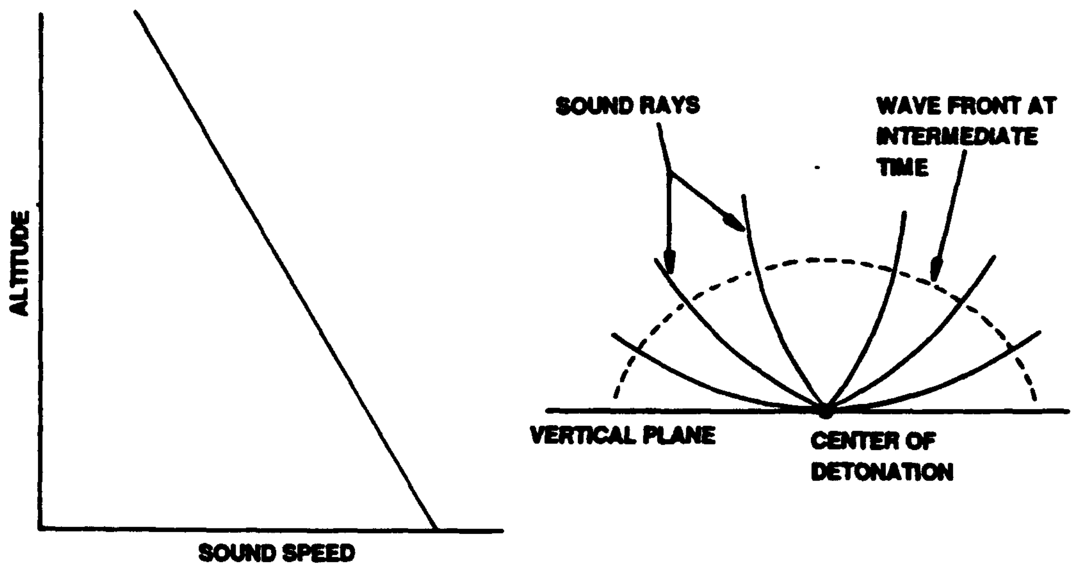

Figure 4. Sound wave propagation from a detonation on the earth surface with a negative sound velocity gradient.

Figure 5 presents a case where a single positive sound velocity gradient is present. All of the sound rays in this case will be turned by the gradient back to the earth's surface. The ray with the smallest departure angle will reach the earth's surface first and at the shortest distance from the center of the detonation. All other rays must follow a longer path and, therefore, will reach the earth's surface after longer times and at greater distances as their departure angles above the horizon increase. The returning sound rays will reflect from the earth's surface, propagate in a curved path, and again return. While the rays lose intensity on reflection, they are refracted again by the positive velocity gradient and combine with other rays whose initial departure angles are greater. This combining of sound rays constitutes an enhancement of detonation effects (greater overpressure) in the far field. The amount of energy lost by the rays on reflection depends on the type of terrain present. The most energy is lost when the terrain features include such things as grass, trees, and buildings. Practically no energy is lost when the terrain is water; hence, the perception that sound travels well over a water surface. Whenever there is a situation where the sound rays are turned back to earth, it is said that an atmospheric inversion is present.

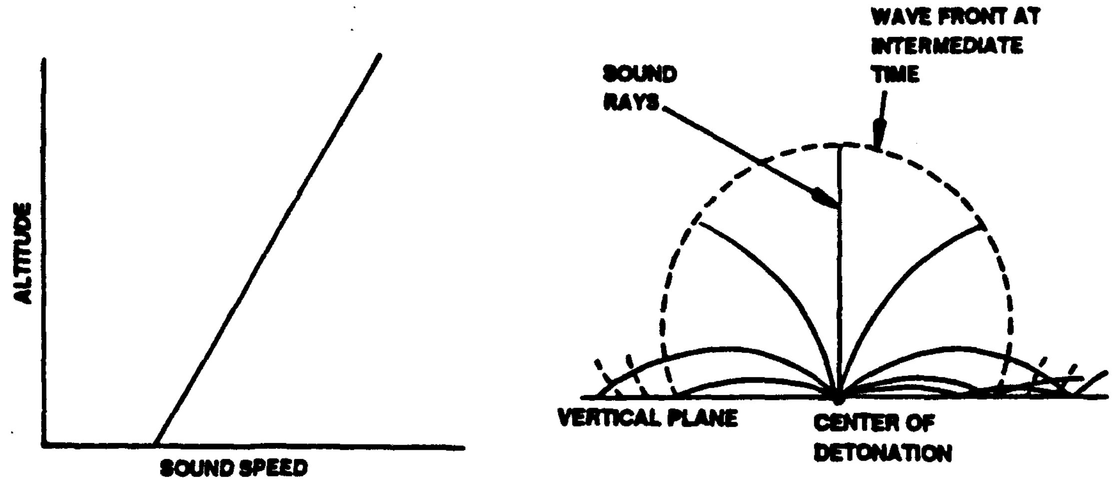

Figure 5. Sound wave propagation from a detonation on the earth surface with a positive sound velocity gradient.

Figure 6 presents the case where a positive sound velocity gradient is present next to the earth's surface with a negative sound velocity gradient above. In this case, the rays are turned earthward while traveling in the positive gradient and will reflect providing they do not reach the negative gradient. On reaching the negative gradient, the rays will turn upward and will not reflect. Consequently, a distance from the detonation center will exist beyond which none of the rays will return to earth. That distance is referred to as the "limiting range." The determining factor as to whether a ray will reach the negative gradient is its departure angle.

Another type of atmospheric condition is presented in Figure 7. In that case, a negative sound velocity gradient is present, above which is a positive gradient. All of the sound rays will be refracted upward away from the earth's surface while propagating through the negative gradient. After which they will be refracted back down toward the earth's surface by the positive gradient. While propagating again through the negative gradient, the rays will tend to spread outward away from the center of detonation. The combined effect of departure angle and thicknesses of the gradients will cause many of the rays to reach the earth's surface at the same distance from the center of detonation. This can constitute a large

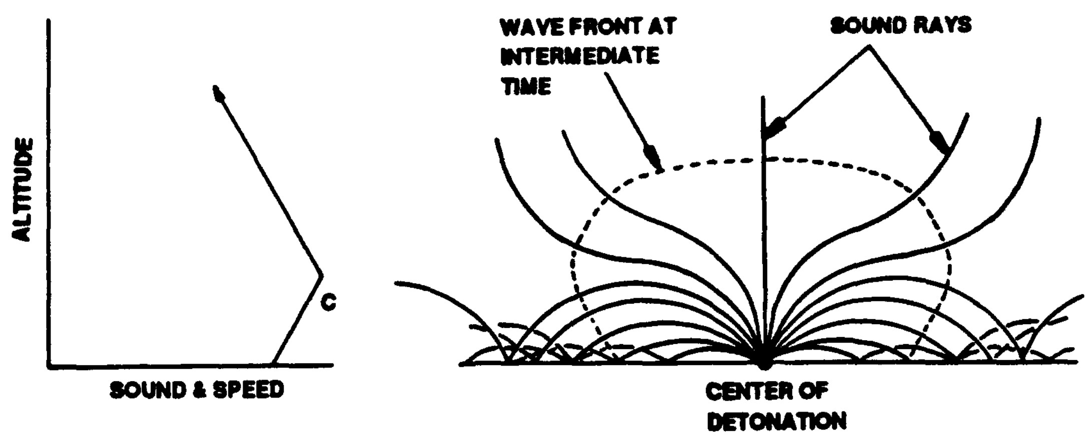

Figure 6. Sound propagation from a detonation on the earth surface with a positive sound velocity gradient below a negative sound velocity gradient.

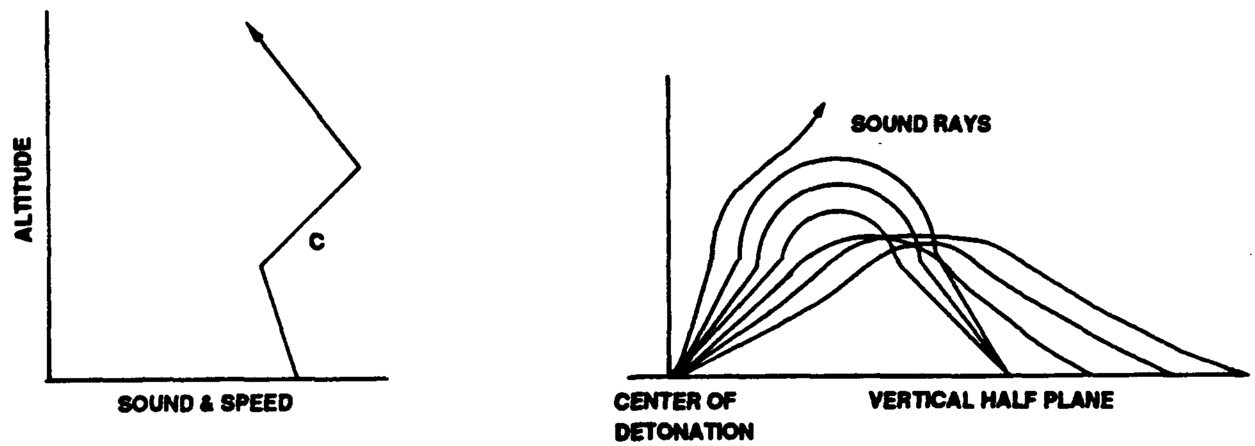

Figure 7. Sound propagation from a detonation on the earth surface with a negative sound velocity gradient below a positive sound velocity gradient.

enhancement of intensity at that location. This result is referred to as a "focus" and the action is referred to as "focusing." This condition is the most severe enhancement of the sound intensity. As a consequence of this type of condition, there is a region of relative silence between the center of detonation and the focus.

2.1.2 Perkins Procedure for Predicting Overpressure in the Far Field. The problem of predicting overpressure in the far field due to detonations was studied by Beauregard Perkins in the early 1960s (Perkins and Jackson 1964). After describing the physics of sound travel, he indicated overpressure multiplication factors that could be used in increasing the prediction above base values calculated under the assumption the sound velocity gradient were zero. Table 2 presents those multiplication factors for each type of gradient combination. For a single negative gradient, the overpressure intensities of the wave will be reduced from base values to zero in the far field, because all of the sound waves will be reflected up away from the earth's surface; hence, the multiplication factor for this case is zero. For a positive gradient with a negative gradient above, the multiplication factor was deemed to be 5 at all ranges up to the limiting range. In the event a zero gradient exists next to the earth's surface with a positive gradient above, a broad focus of sound rays will be created at which the multiplication factor was deemed to be 10 in the focal area. A weak positive gradient with a strong positive gradient above causes a more concentrated focus at which the intensity factor was deemed to be 25. The most severe level of enhancement is caused by a combination consisting of a negative gradient, above which exists a strong positive gradient. In that case, the multiplication factor at a concentrated focus was deemed by Perkins to be 100. These multiplication factors were derived on the basis of several years of experience. The determinations were made by noting the distance to a particular type of damage and, assuming the minimum overpressure known to produce such damage, a maximum multiplication was calculated. These are approximate factors and there are differing opinions concerning the general correctness of their magnitudes.

The location of the focus (distance from the center of detonation) can be estimated by employing sound ray propagation theory. Perkins and Jackson (1964) used the theory to generated ray paths for the gradient combinations described in Table 2. A complete range of possible sound velocity slopes and gradient combinations for meteorological conditions up to 5,000-ft altitude (87 different cases) were considered. To utilize this database, the initial step is to calculate a sound velocity distribution for the case in question with Equations 2 and 3 and temperature and wind velocity distributions for altitudes up to 5,000 ft (which is provided by the Army reservation against whom the claim is made). With the

Table 2. Perkins' Multiplication Factors for Determining Overpressure Enhancement

Single negative gradient	0 - From origin to limit of observation.
Positive gradient near surface with negative above	5 - Origin to limiting range.
Zero gradient near surface with strong positive gradient above	10 - Focal area only.
Weak positive gradient near surface with strong positive gradient above	25 - Focal area only.
Negative gradient near surface with strong positive gradient above	100 - Focal area only.

slopes of the sound velocity distribution an appropriate case can be chosen from the Perkins' database. If the sound velocity slopes do not correspond to a presented case (the most likely event), the correct focal distance can be ascertained by interpolation. If the distance between the center of detonation and the claimant's damaged property match the predicted focal distance, then the final prediction of overpressure is taken to be the predicted overpressure at that distance assuming no meteorological effects (a base curve) multiplied by the appropriate multiplication factor. If the two distances do not match, then the final predicted overpressure requires additional subjectivity concerning overpressure enhancement or reduction of the base curve prediction outside the focal area.

Several difficulties exist in the utilization of this approach for estimating overpressure. One is that meteorological data up to 5,000-ft altitude are usually not available and, if a set of data are provided, there is usually some question concerning the data's validity. Assuming the meteorological data provided are valid, the execution of the procedure is long and laborious (this could be corrected by computerizing the procedure). Then once the focal distance has been estimated, further error is introduced if the focal distance does not match the actual distance between the claimant's property and the center of detonation. Finally, the multiplication factors suggested by Perkins appear to be too high for the practical purposes of evaluating most claims. The basis for this conclusion is that on those occasions when sound measurements are available in the far field, the Perkins multiplication factors causes the predictions to be much higher than the measurements.

2.1.3 Current Procedure in Use for Predicting Overpressure in the Far Field. The current procedure used to predict overpressure in the far field due to detonations is essentially that reported by Raspet and Bobak (1988). The approach is to initially estimate an overpressure level at the appropriate distance (the distance between the detonation and the claimant's damaged property) for a 0.454-kg (1-lb) TNT charge, and then to adjust the overpressure level for total charge weight, type of charge, ground reflection for a surface burst, and finally, a reduction if the charge is buried. The advantages of the procedure, from the claims evaluation perspective, are completeness and simplicity. A prominent feature of the total approach is the deliberate intention to predict overestimates to ensure that the claimant has received the benefit of any doubt.

• Free Field Overpressure Due to 0.454-kg TNT Charge. In the near field, the peak overpressure as a function of distance from the center of the detonation has been measured extensively and is well established. A curve of free-field overpressure versus distance for a 0.454-kg charge of TNT for the near field is presented in Figure 8 (a) (Lehto and Larson 1988). Free field is defined to mean that the blast propagation is not obstructed or enhanced by atmospheric conditions and there are no physical effects from obstructions or boundaries such as a ground surface. This base curve can be scaled to other charge weights by multiplying the distance (range) for a desired overpressure by the cube root of the ratio of the charge weights. For example, if the distance corresponding to a specific pressure level is desired when the charge weight is 454 kg (1,000 lb), then the distance given in Figure 8 (a) for that overpressure needs to be multiplied by the cube root of 454/0.454 or 10. Figure 8 (b) presents overpressure levels in the far field which were obtained by extrapolating the near field data theoretically. The curve was extended further on the basis of data obtained in the Project BANSHEE HE test.

• Accounting for Arbitrary Explosive Type. For explosives other than TNT, it is necessary to convert from the type of charge in question to an equivalent weight of TNT prior to using Figure 8. This is done by multiplying the charge weight by a value referred to as the "efficiency factor" (overpressure). Table 3 presents a number of various types of explosives and their corresponding efficiency factors relative to TNT. Similarly, Table 4 presents some common demolitions used by the Army and their total equivalent TNT weights.

• Charge Weight Increase Due to Ground Surface Reflection. Since the basic curve in Figure 8 is for a free-air burst, the charge weight needs to be corrected to account for the effect of blast reflection when the charge is detonated on the ground surface. The magnitude of correction needed can be

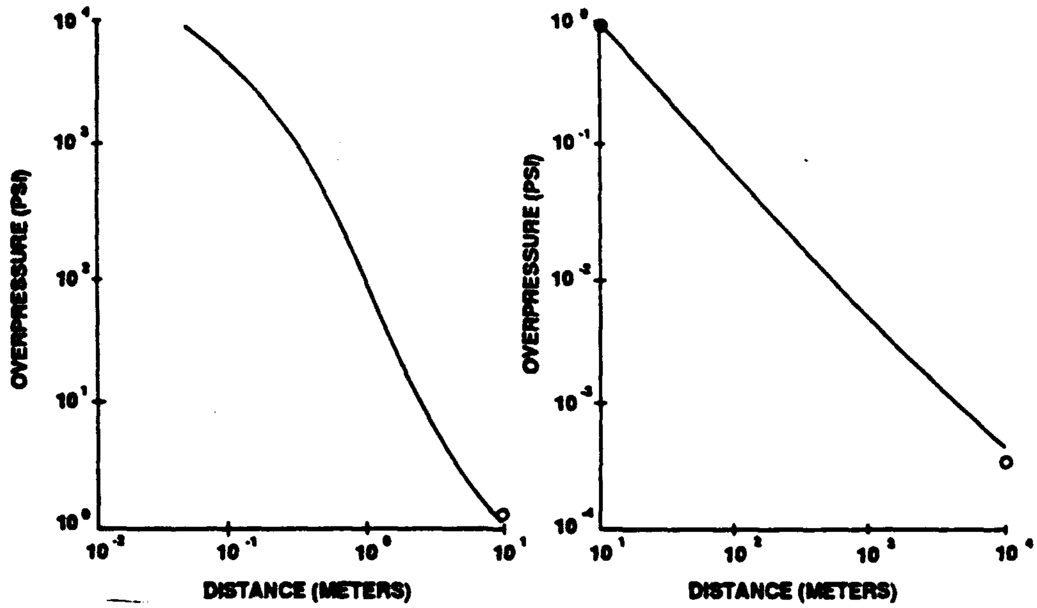

Figure 8. Peak free field overpressure vs. distance due to the detonation of a 0.454-kg (1-lb) charge of TNT at sea level: a) near field and b) far field.

Table 3. Efficiency Factors for Calculating Equivalent TNT Weights

Explosive	Efficiency
TNT	1.00
Tetrytol, M1, M2	1.20
Composition C3, M3, M5	1.34
Composition C4, M5A1, M112	1.34
Ammonium nitrate (cratering charge)	0.42
Sheet explosive, M186, M118 (demolition Charge)	1.14
Military dynamite (DYN), M1	0.92
Straight DYN; (Com.) 40%, 50%, 60%	0.65, 0.79, 0.83
Ammonia DYN; (Com.) 40%, 50%, 60%	0.41, 0.46, 0.53
Gelatin DYN; 40%, 50%, 60%	0.42, 0.47, 0.76
PETN	1.66
Tetryl	1.25
Composition B	1.35
Amatol 80/20	1.17
Black powder	0.55
Nitrostarch	0.80
Pentolite	1.27

Table 4. Common Demolitions and Their Equivalent TNT Weights

Demolition Kit, Bangalore Torpedo	
M1A1 4.1 kg Amato/0.5 kg TNT Booster	15.2 kg (33.5 lb)
M2A2 4.8 lb Comp B4/0.5 kg A-3 Booster	7.0 kg (15.4 lb)
Charge Demolition: Block, 40-lb Cratering	
13.6 kg Ammonium Nitrate/4.5 kg TNT	10.3 kg (22.7 lb) + Booster Charge
Shaped Charge Demolition	
M2A3 (15 lb) 4.3 kg Comp B/0.9 kg Pentolite	6.9 kg (15.2 lb)
M2A4 (15 lb) 5.2 kg Comp B/0.05 kg A3	7.0 kg (15.4 lb)
M3 (40 lb) 12.8 kg Comp B/0/8 kg Pentolite	18.3 kg (40.3 lb)
M3A1 (40 lb) 13.8 kg Comp B/0.05 kg A3	18.6 kg (41 lb)

visualized by noting that when a detonation occurs on a perfectly reflecting surface, resulting overpressure levels as a function of distance are such that the charge weight appears doubled. In reality, however, a typical ground surface is not a perfectly reflecting surface because some of the energy is lost in the cratering process; thus, the correction factor should be less than 2. It has been estimated that for a typical surface the factor is about 1.8, and, if the surface is soft, the correct factor might be more nearly 1.5. In the evaluation procedure, the assumption taken is that the ground surface is typical, thus the charge weight is multiplied by 1.8. On rare occasions, the value of 1.5 might be used. In the event the charge is assumed to be buried, then the ground surface reflection correction is not applicable, and the charge weight is not changed.

• Peak Overpressures for Free-Air 0.454-kg Burst. The peak overpressure level in decibels as a function of distance in kilometers curves for a free-air detonation of a 0.454-kg (1-lb) charge of "standard" TNT are presented in Figure 9. The base curve constitutes those levels when meteorological effects are not considered. The probable focus curve, relative to the base curve, is a factor of 1.8 in the range of 0 to 27.4 km (0 to 90 kft), a gradual change in factor from 1.8 to 3 in the range of 27.4 to 45.7 km (90 to 150 kft), and a factor of 3 in the range of 45.7 km (150 kft) and further. The maximum overpressure curve relative to the base curve is a factor of 2 in the range of 0 to 0.61 km (0 to 2 kft), factor of 4 in the range of 0.61 to 3.05 km (2 to 10 kft), factor of 8 in the range of 3.05 to 45.7 km (10 to 150 kft), and a factor of 15 in the range of 45.7 km (150 kft) and further.

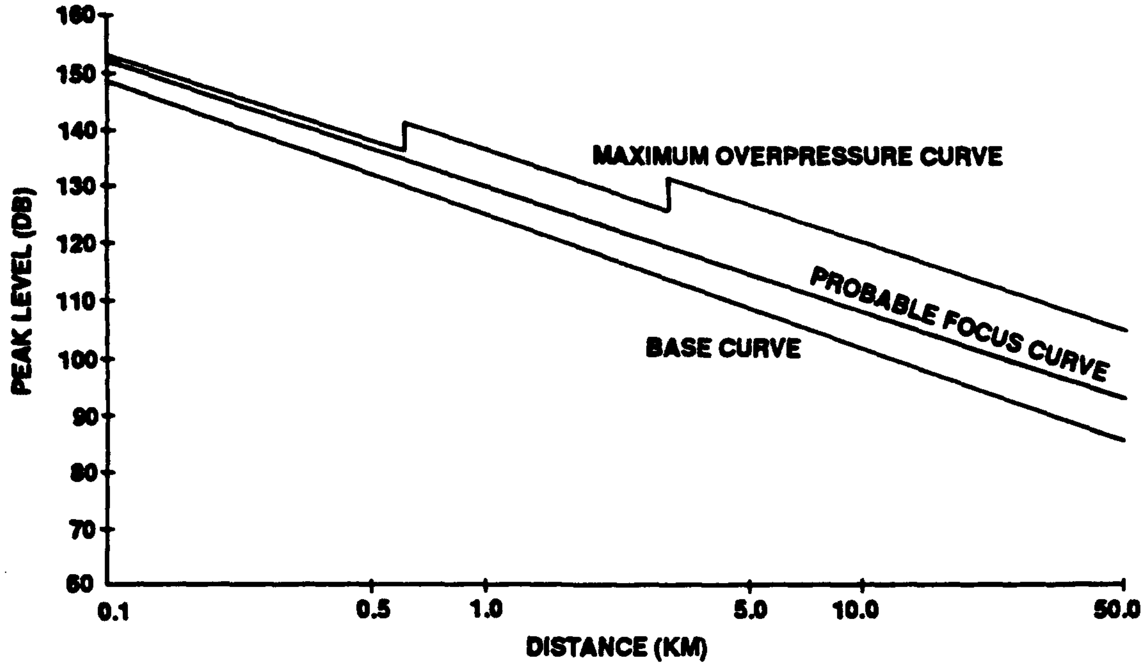

Figure 9. Peak overpressure vs. distance due to the detonation of a 0.454-kg (1-lb) TNT charge in free-air with enhancements due to meteorological effects.

For most claims, it is assumed the claimant's property was subjected to maximum focus conditions and, therefore, the maximum overpressure curve is used. This helps to ensure that the overpressure level obtained is a worst-case prediction. The other curves are used when specific information is provided which indicates that the maximum overpressure curve should not be used. Such information could be a reliable meteorological data curve that indicates a single negative or a single positive sound velocity gradient was present. Once the decision is made as to which of the curves to use in an evaluation, an overpressure level is read at the distance equal to that between the center of detonation and the claimant's property.

• Peak Overpressure Level Adjusted to an Equivalent TNT Charge Weight. The next step is to add a factor to the overpressure level to account for the total charge weight. This is accomplished by using Figure 10, which contains a plot of the correction factor in decibels vs. the equivalent charge weight in kilograms. As mentioned above, if the detonation is a surface burst, then the charge weight is increased by a factor of 1.8 to account for ground surface reflection; but, if the charge is buried, that is not done. To account for the type of charge detonated, the charge weight is multiplied by the appropriate efficiency factors as given in Tables 3 or 4. This adjusted overpressure estimate constitutes the predicted overpressure level at the claimant's property provided the charge is not buried.

Figure 10. Weight correction factor.

• Peak Overpressure Level Adjusted to Account for Depth of Burial. The estimation of a correction factor for buried charge detonations which is subtracted from the peak overpressure is based on Figure 11 and the depth of burial. Figure 11 presents a curve which represents a reduction in peak overpressure level (dB) as a function of a scaled depth ($d/w^{(1/3)}$), where d is the depth in meters and w is the equivalent TNT charge weight. The parameter d is the depth from the ground surface to the top of the charge.

• Conclusion. This concludes the procedure for predicting the overpressure pulse as a consequence of detonations on the surface of the ground or if the charge is buried. Other factors such as detonation distance above the ground surface or significant terrain features are accounted for subjectively if the analysis indicates further refinement is needed. Such a refinement might be considered justified in those cases where the predicted overpressure level at the claimant's property is near the damage threshold for the specific damage claimed. That is, if the predicted overpressure level is slightly below the threshold which would mean the claimant would not be compensated, collateral technical factors could be considered to justifiably increase the predicted overpressure level above the threshold.

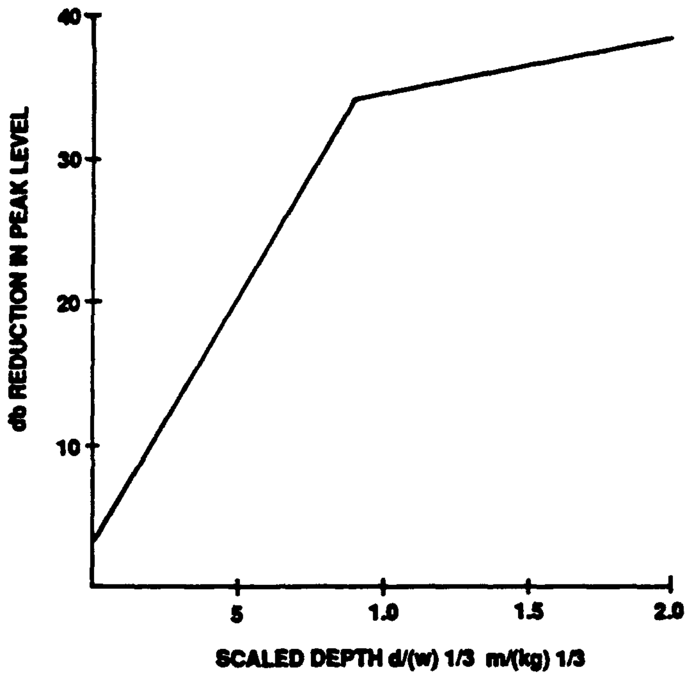

Figure 11. Buried correction - peak overpressure level vs. scaled depth.

2.2 Overpressure Due to Muzzle Blast. There are three sources for air disturbance to be generated during the firing of artillery pieces: (1) detonation of the projectile on impact (if it is an HE shell), (2) bow wave cause by the interaction of the shell with the atmosphere as it moves at supersonic speeds, and (3) muzzle blast. The procedure for predicting overpressures in the far field due to detonating HE shells is that used for any other HE detonation and which has already been described. The magnitude of the overpressures generated as a consequence of the hypersonic bow wave formation can be significant in the region between the firing point and the impact point which confines that component within the areal bounds of the Army reservation, and therefore is of no consequence. Thus, only muzzle blast is discussed further in this section.

Muzzle blast is caused by the sudden release of gases from the muzzle following the departure of the round being fired. These gases are formed as a consequence of the burning of propellent in the weapon's chamber and are under a very high pressure, which is required in order to propel the round to its target. The levels of overpressure as a function of distance beyond the weapon's muzzle reach their highest values in the direction the weapon is firing. Taking the direction of fire as 0°, the overpressure decreases as the angle increases to 180° (back of weapon). However, in those cases when a muzzle brake is employed, the magnitude of the overpressure in the 0° (direction of fire) is less and values at other directions are greater. This is demonstrated by Figure 12 (Schomer, Little, and Hunt 1979). Figure 12 (a) presents the overpressure level magnitudes for the towed 155-mm howitzer which does not deploy a muzzle brake. The levels are greatest toward the direction of fire. Figure 12 (b) presents the same data for the self-propelled howitzer which does deploy a muzzle brake. The overpressure magnitudes are essentially the same in all directions. To be more certain that the prediction will not be underestimated in the claims evaluation process, the procedure for predicting muzzle blast is based on data measured in the direction of fire from a weapon without a muzzle brake.

The procedure described below for predicting overpressure in the far field is essentially that presented by William Taylor (unpublished). Taylor discussed a series of gun firings conducted to ascertain relationships between overpressure as a function of distance as affected by propellant charge weight and gun tube variables. The gun tube variables included length, elevation, and azimuth (angle in the horizontal plane). A portion of the data consisted of overpressure measurements taken during the firing of a 120-mm gun. These selected data were collated according to the overpressure levels (db) as a function of distance (km) above which 1% and 50% of the measurements fell. Figure 13 presents the two curves which represent these results. The curves are designated as 1% Exceedance and 50% Exceedance, respectively. In the generation of these data, the weapon caliber, propellent charge weight, and azimuth angle of the gun tube were constant, so that the variation of overpressure measurements at specific distances were due to variations in meteorological conditions and gun tube elevations. In the evaluation procedure, we must predict the maximum overpressure possible because of our inability to account for the many variables involved. Therefore, the 1% exceedance curve was chosen as the basis for predicting overpressure levels at the claimant's property.

The results of the prediction procedure are maximized even further by considering data from 155-mm howitzer firings conducted at the Aberdeen Proving Ground, MD. In that case, 100 inert rounds were fired in a period during which no other firing activity was in progress. Overpressures were measured at approximately 9 km distance from the muzzle and in a 39° azimuth angle. This experimental data point, consisting of the average peak overpressure measured, is a level which exceeds the 1% exceedance curve for the 155-mm howitzer as is shown in Figure 14. The 1% exceedance curve was obtained by scaling from the data for the 120-mm gun by the ratio of calibers. This scaling procedure is plausible because, for replica scaling, length varies as the caliber. Since the data point in question exceeded the 1% exceedance curve, further maximization was achieved by translating the 1% exceedance curve onto the 155-mm data point to create another curve referred to as "maximum muzzle blast." None of the test

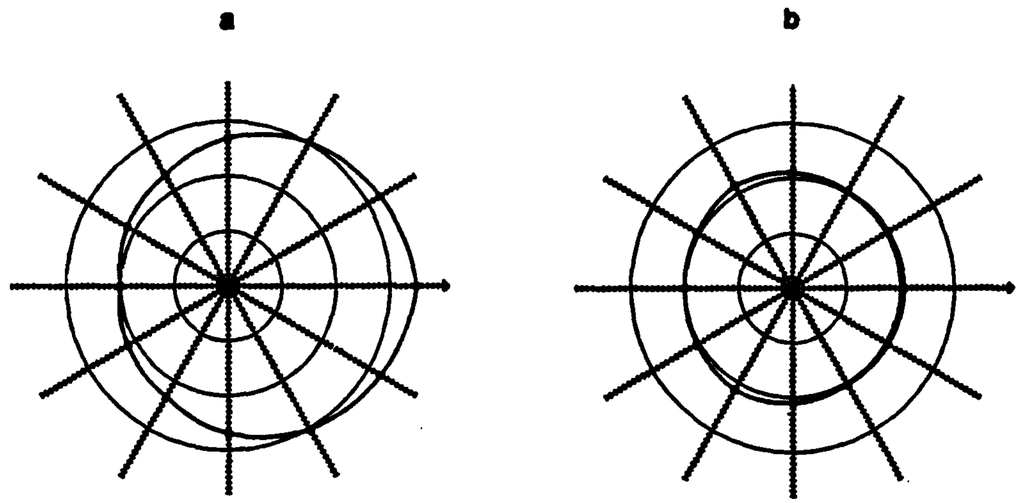

Figure 12. Direction pattern of muzzle blast for a 155-mm howitzer: a) without a muzzle brake and b) with a muzzle brake.

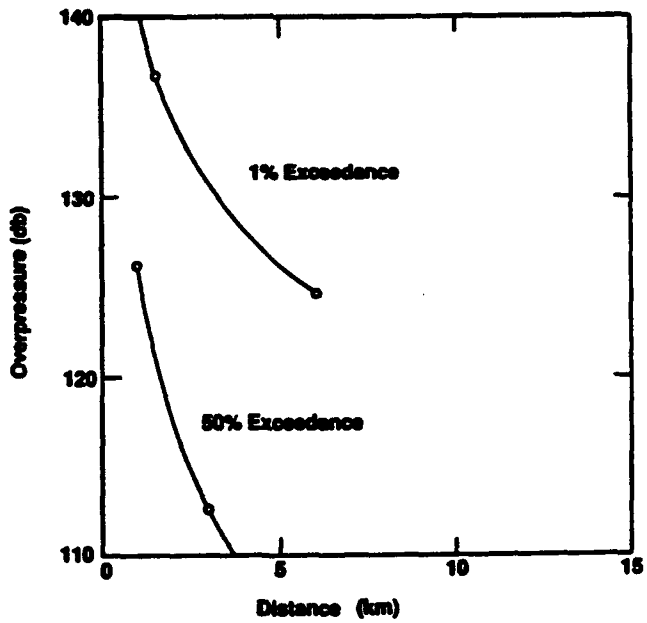

Figure 13. Overpressure due to muzzle blast from a 120-mm gun as a function of distance at the 0° azimuth angle (front).

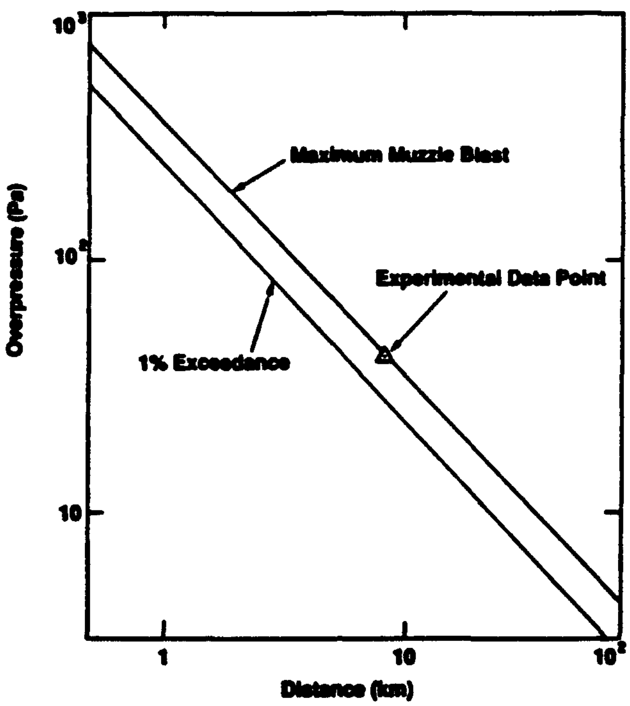

Figure 14. Overpressure due to muzzle blast from a 155-mm howitzer.

measurements were made over water. However, because of the strong bias toward choosing the maximum overpressure data as the database, it is believed that peak overpressure predictions when water is involved are fair to the claimants in those cases. Figure 15 presents maximum muzzle blast (worst case) prediction curves for four different size weapons. These were obtained by scaling the 155-mm maximum muzzle blast curve to the others. The use of these data in overpressure calculations yields predictions which are considered to be worst cases in favor of the claimants.

2.3 Ground Motion Due to Detonations. Another mechanism which theoretically has a potential for causing damage is vibrations due to ground motion. The parameter used to gauge the strength of such a disturbance is particle motion measured in inches per second (in/s). At locations close to the energy source, the particle motion level can be very high, but the ground shock strength dissipates rapidly as it propagates through the earth and becomes negligible prior to reaching a typical claimant's residence. Ground motion can also be created by energy transfer from an air overpressure shock wave propagating over the ground surface. But in that case, to have significant ground motion, air overpressure levels would have to be extremely high, a situation not possible in the far field. Therefore, although included in the technical analyses, ground shock is seldom, if ever, the cause of damage to private property.

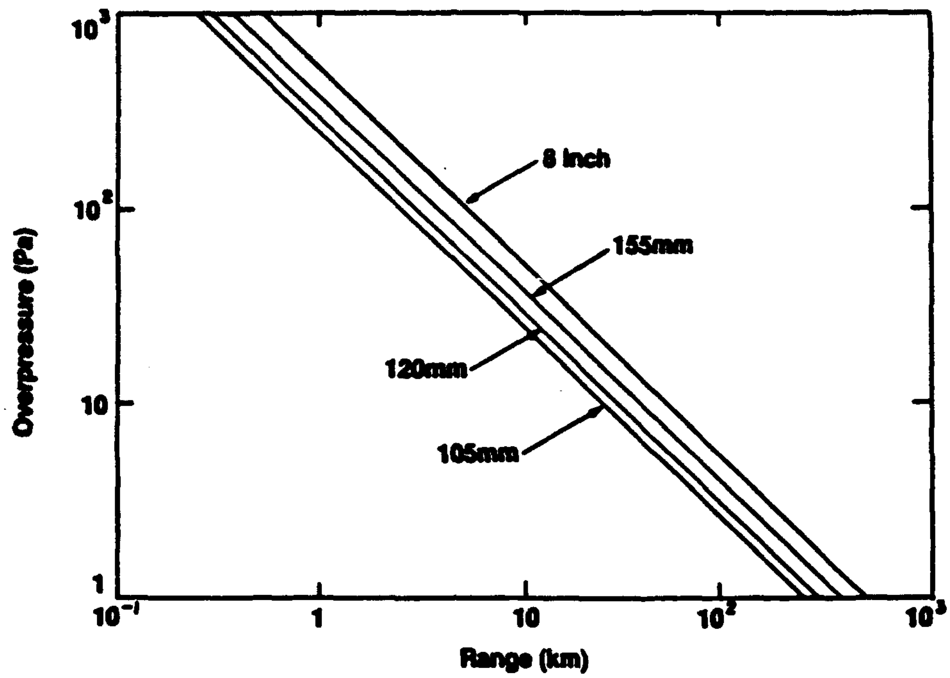

Figure 15. Worst-case overpressure due to muzzle blast from selected army weapons as a function of distance.

To predict ground motion levels due to a surface detonation, the following equation derived from empirical data is available (Siskind et al. 1980):

$$PPV = 5.349X10^{15} \; (R/W^{1/3})^{-5.354} \quad . \tag{4}$$

Where:

PPV = Peak particle velocity
R = distance from ground zero (ft),
W = high explosive charge weight (lb), and
PPV = peak particle velocity (in/s).

For ground motion, where the charge is entirely buried with no venting, the following equation is used (Johnson et al. 1988):

$$PPV = 1{,}200 \; (R/W^{1/3})^{-2.7} \quad . \tag{5}$$

Where:

PPV = peak particle velocity (cm/s).

R = distance from ground zero (m), and

W = high explosive charge weight (kg).

Equation 5 was the result of analyzing the measurements from a series of tests done during the 1980s where the explosives were buried in soft limestone and chalk. It was found that these tests conducted in soft material provided higher ground motion levels than predicted by relations which were based on tests conducted in harder material. As a consequence of these higher predictions, it was decided to use Equation 5 whenever no atmospheric venting is assumed for buried detonations.

3. DAMAGE CRITERIA FOR RESIDENTIAL PROPERTY

3.1 Damage Thresholds Attributable to Overpressure.

3.1.1 Threshold for Structural Damage. The U.S. Army has not studied to any appreciable extent damage occurring in the far field due to artillery or demolitions. Consequently, outside sources of data and information have been exploited for the purpose of establishing acceptable air overpressure damage criteria for residential property. This includes aircraft sonic boom studies, since the damage effects from sonic boom are similar to those from blast overpressure pulses.

In order to reduce the amount of time required for performing many technical evaluations, a threshold level for structural damage is sought. The determination of a threshold for structural damage to residential property in the far field has not been a precise or easy task. It has been reported that despite widely varied source characteristics, assumptions of damage probabilities, experimental designs, and differing interpretations, there appears to be a consensus that damage is improbable below approximately 205 Pa (140 db) (Siskind et al. 1980b). However, for purposes of damage claim evaluations, 138 Pa (136.5 db) is assumed to be the threshold for structural damage. Therefore, in an evaluation of a claim of structural damage when the predicted overpressure level to which the property could have been subjected is less than 138 Pa (136.5 db), the analysis is terminated and the conclusion is drawn that the Army was not responsible. If the predicted level is above 138 Pa, then additional factors are considered to reach a final conclusion.

3.1.2 Window Glass. Numerous claims submitted include window glass breakage. The sizes of window panes involved have ranged from the usual sizes found in residential property up to large plate glass windows found on business properties. The dimensions of interest include width, length, and thickness. In addition to dimensional parameters, the vulnerability of window panes depends on glass quality and installation methods. Breakage can be affected by how loose the window pane is relative to the window sash and its stress level at the time it is being subjected to the induced vibrations caused by the overpressure pulse. Due to the many variables involve, it has been difficult to develop a systematic procedure for evaluating claims which include glass breakage. However, a definite procedure for estimating a safe overpressure threshold for window glass is required in order to maintain consistency and to conserve evaluation time. Consequently, it was decided to depend on the following criterion for window breakage which is based on sonic data (Siskind et al. 1980b):

$$p_0 \, (a/h)^2 \geq 0.8 \times 10^6 \; lb/ft^2 \quad . \tag{6}$$

Where:

p_0 = overpressure (lb/ft^2),
a = side of an approximately square window, and
h = window thickness (same units as a).

With a/h generally less than 330, the safe maximum overpressure is 360 Pa (145 db).

3.1.3 Damage Levels for Selected Structural Components. A summary of threshold levels for specific kinds of damage are presented in Table 5. Most of the results are due to sonic boom tolerance tests conducted at White Sands, NM, with several values due to sonic boom tests conducted in Oklahoma City. Also included are thresholds levels for damage due to material fatigue where the overpressure must be applied continuously for periods extending into numbers of minutes. These are significant with regard to civilian damage claims because many times the claimant believes damage was due to repeated applications of some kind of Army-caused vibrations. Since overpressure pulses caused by Army firing activities are always concluded in time periods in the order of milliseconds, these data shows that such a view is usually not valid. The data provided in Table 5 serve as a basis for evaluating claims, but many times the residential component cited is not listed. In those cases the item must be compared with a similar item in the table and a subjective judgement made.

Table 5. Overpressure Threshold Criteria for Structural Damage

Interior	Pascals (Pa)
Plaster on wood lath	160
Plaster on Gyplath	360
Plaster on expanded metal lath	765
Plaster on concrete block	765
Plaster, new	260
Plaster, cured	500
Nail popping	250
Gypsum board (old-cracks)	220
Gypsum board (old-loose paint flaking)	460
Gypsum board, 1/2-in (nail popping)	510
Gypsum board (new-cracks)	765
Bathroom tile (old)	213
Suspended ceiling (new)	186
Exterior	
Brick (cracks)	896
Glass door (loosened)	896
Mullions (twisted)	427
Molding (popped)	896
Stucco (new)	234
Light-weight superstructure	10,000
Concrete	34,000
Wood frame wall (fatigue, 80 min.)	285
Roof (fatigue, 20 min.)	360
Concrete wall, 8-in thick (fatigue, 10 min.)	900

3.1.4 Damage Attributed to Falling Objects. Air overpressure pulses can cause cyclic movement of residential walls referred to as "midwall motion." Accelerations that can cause light objects to rattle and be displaced vary from 0.1 to 1.0 g, depending on shape, center of gravity, and natural frequencies of the vibrating items. A wall acceleration of 0.5 g, which corresponds to approximately 75 Pa (133 db), is considered sufficient to shake such items (Siskind et al. 1980b). However, in the evaluations of damage claims due to displacement of light objects, it is assumed that a 68-Pa overpressure level is sufficient to judge that the Army was responsible.

3.2 Damage Threshold Attributable to Ground Motion. A comprehensive discussion of residential structural response and damage produced by ground vibration from HE detonations was provided by the Bureau of Mines (Siskind et al. 1980a). The discussion points out that rather than considering ground motion in terms of displacement and acceleration for predicting damage, that a superior physical parameter is particle velocity in inches/second (in/s). The reason stated was that particle velocity is more independent of the blast wave frequency. It reiterated a result, taken from an earlier study, that 2.0 in/s particle velocity is a safe value damage criterion for residential damage and that this value is frequency independent over the wide range of 2.5 to over 400 Hz. It was remarked in the discussion that 0.75 in/s is a good minimum criteria for modern construction and that the 2.0 in/s is justified for high-frequency blasts which is the case in the general firing activities by the Army. However, in evaluating claims, the policy is to use 1 in/s particle motion as the threshold for structural damage, which means that if the ground motion or particle velocity predicted does not exceed that value, the analysis is terminated and the conclusion made that the Army was not responsible for the claimed damage.

4. TECHNICAL EVALUATION PHILOSOPHY

The basic philosophy governing technical evaluations is to always apply a conservative approach such that the Army can easily defend its decision if the claimant decides to appeal. This conservative stance is maintained by utilizing a procedure which maximizes overpressures (or ground motion) at the claimant's damaged property (in the far field); that minimizes the sure-safe damage thresholds; and finally, whenever there is uncertainty in reported circumstances or the result is marginal, the decision is to favor the claimant.

Initially a worst-case analysis in favor of the claimant is performed. That is, using the distance between the claimant's damaged property and the Army activity, the overpressure level is predicted with the assumption that meteorological conditions are worst case. That overpressure level is compared to the threshold for the type of damage claimed. If the predicted worst-case overpressure level is less than the threshold overpressure (or ground shock) for that type damage, then there is no point in continuing the analysis, because further analysis cannot result in a greater overpressure. For that result, the conclusion is drawn immediately that the Army was not responsible. If the predicted level exceeds the threshold, then an attempt is made to improve the prediction for the purpose of achieving a more accurate result (than worst case) in fairness to the Army. The continuation would consist of incorporating additional factors such as meteorological data. If a repeat comparison with the thresholds shows that the prediction falls below the threshold, then the conclusion is drawn that the Army was not responsible. If the new prediction falls above the appropriate threshold, then characteristics of the damage claimed must be studied with respect to the available threshold database and a specific conclusion drawn. At times the final conclusion requires considerable subjectivity, but the policy is always to favor the claimant. In instances of unusual circumstances, the evidence might be apparent that the Army was responsible for the claimed damage. These are rare, because the Army is continually monitoring its firing activities to find ways to reduce levels of disturbance to surrounding communities.

5. DATA REQUIRED FOR TECHNICAL EVALUATION

The technical evaluation consists of applying the methodology described above to data provided by the claimant and Army personnel from the Army reservation involved. Army policy, procedures, and information required for the purpose of conducting a technical evaluation are described in Department of the Army Pamphlet 27-162. The claimant describes the basis for the claim on Army Form 95-107. Instructions on the form ask for a brief statement of known facts and circumstances surrounding the damage, identification and location of the property involved, and suspected cause. The claimant is asked to give the date and time the incident occurred in order that the Army can determine the precise firing activity which was in progress when the damage occurred. In some claims, the damage is presumed by the claimant to have occurred in an accumulative fashion over a period of time which might extend to several months or years. The brief information provided by the claimant can be supplemented with a personal interview and damage inspection by an Army representative. This interview serves to clarify the description of the damage, verify when the damage occurred, and ascertain physical evidence. An important form of physical evidence is photography, which can be enhanced by a supplementary physical description of the damage. In the case of window glass breakage, the size and thickness of the window panes must be provided to determine the safe overpressure threshold. In general, the more detail provided, the greater the probability the technical evaluation will yield a final conclusion which is fair to both the claimant and the Army.

It is essential that the technical evaluator know the relative positions of the claimant's damaged property and the Army firing activities. The most convenient method is for the Army to provide an official map of the Army installation involved and the surrounding areas. The claimant's damaged property, artillery firing points, artillery impact areas, and demolition areas must be identified on the map. Once a map of a particular Army reservation has been provided, then only coordinates of positions need be supplied in subsequent claims involving that reservation.

Actual Army firing activities conducted during the time period in question are required. The most difficult aspect of this, in practice, is when only a copy of the firing range record is provided. The quality of these records varies greatly from one Army installation to another. In many cases, a kind of symbolism is used which only local firing range personnel are able to interpret. The evaluation process could be enhanced if appropriate firing record information were provided in clear, unmistakable terms.

Table 6 lists information which must be extracted from firing records or obtained in some other manner. In all cases, weather conditions such as cloud cover, temperature, and wind velocity should be included. In the case of artillery, the size rounds fired, firing positions, impact areas (if rounds are not inert), and time intervals between firings should be provided. Demolition activities require knowing the total charge weight of each detonation (including detonator), number of individual charges, relative position between charges, and time interval between detonations. For DEMIL operations, the depth of burial, weight of charges, relative locations of charges, and time intervals between detonations are needed. In the event there are information gaps, the evaluator must assume the most likely scenario and, in general, make choices tending to favor the claimant.

Table 6. Minimum Firing Range Data Required

Artillery	Demolition
Size rounds fired. Firing positions (for muzzle blast effects). Impact area (live rounds). Time interval between firings.	Weight and type of explosive. Number of charges. Time intervals between detonations.
DEMIL	**Meteorological Data**
Depth of burial. Weight and type of explosive. Number of charges. Time interval between detonations.	Temperature and wind velocity up to 5,000-ft altitude.

6. SUMMARY

Technical evaluations of private property damage claims against the Army are based upon a philosophy designed to place the Army in good defensive posture in the event the decision is appealed. This is reflected in overestimating predicted overpressures and underestimating damage criteria which inherently causes the evaluation to favor the claimant. The tendency is further enhanced by giving the claimant the benefit of the doubt whenever uncertainty in available facts exist.

The evaluation procedure described is referred to as the "current procedure," because for two reasons it will change in the future. It is certain that change will occur when new information or understanding is obtained by the evaluator. Also, when a new evaluator is chosen, change will be necessary to reflect the new evaluator's opinions, understanding, and preferences, because these must be respected if this approach for resolving damage claims is to be successful.

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